The experimental future of Neutrino Oscillations

Mario Campanelli
Institut für Teilchenphysik ETH Zürich Switzerland

After the recent experimental results on neutrino oscillations, some shape starts to emerge from the puzzle. However, the situation is still far from being clarified. First of all, accommodating all experimental results in a single and simple framework is not possible, and the possibility of sterile neutrinos entering the oscillation process has not been ruled out. Moreover, new questions arise that the presently-available data, nor those that will be available in a near future, will be able to answer. In this paper some of these problems will be discussed, as well as the experimental guidelines for their clarification.

1 Introduction

At present, there are three classes of experiments where effects that could be interpreted as indications of neutrino oscillations have been seen. They are, in decreasing order of robustness of the result:

- **Atmospheric neutrinos** Several different experiments [1] are consistent in indicating an angle-dependent disappearance of muon neutrinos, with maximal mixing and a mass difference squared of the order of $\Delta m^2 \approx 3 \times 10^{-3} eV^2$. The angular dependence of the deficit is a clear smoking gun for oscillations, since it is incompatible with other effects (i.e. neutrino decay).

- **Solar neutrinos** A large deficit in the number of electron neutrinos observed with respect to the standard solar model has been found by several experiments in different energy ranges[2]. It can be interpreted as oscillations involving electron neutrinos with a mass difference squared around $10^{-5}, 10^{-7}$ or $10^{-10} eV^2$ (with the first value preferred by the latest results) Independent measurements on the solar activity (like heliosismology lines) seem to validate the robustness of the solar model, but no unambiguous indication for oscillation has been found. For space reasons, future experiments for solar neutrino detections will not be discussed here.

- **Accelerator neutrinos (LSND)** An excess of electron events in a ν_μ beam has been observed by the LSND [3] collaboration for over 5 years. This result was not confirmed by the KARMEN II [?] experiment, but a small region of the parameter space is still allowed by the combination of the two experiments, for $\nu_\mu \to \nu_e$ transitions with a mass difference squared around $0.1 - 1.0 eV^2$.

The data from atmospheric neutrinos largely favor $\nu_\mu \rightarrow \nu_\tau$ transitions; if however the ν_e disappearance in solar neutrinos is interpreted as result of $\nu_e \rightarrow \nu_\mu$ transitions, the allowed parameter space would be very far from the indications of the LSND experiment. In any case, no matter how data are interpreted, the existence of three independent mass differences is not compatible with oscillation involving only three neutrino families, since in this case only two independent mass differences would be involved. If all experimental results have to be explained in terms of neutrino oscillations, it is mandatory to assume the existence of a fourth neutrino, that would be sterile, i.e. would have a very small coupling with the Z boson, otherwise its existence would have emerged from LEP data.

2 Testing the LSND result

As we have seen, out of the three present indications for oscillations, the LSND claim still awaits independent confirmation. And since its interpretation as neutrino oscillations requires the introduction of the sterile states, it is obvious that confirming or disproving LSND is one of the crucial issues of future experimental neutrino physics. This will be the main goal of the MiniBOONE experiment [5], expected to start data taking in December 2001. Neutrinos will be produced by protons from the Fermilab booster ($< E_p >$=8 GeV), and will have a broad spectrum around E_ν=1 GeV. The detector will be a large sphere of 807 (445 fiducial) tons of scintillating material (mineral oil), read by 1280 8-inch phototubes. Like LSND, the aim is to search for electron appearance in a beam primarily composed of ν_μ; however there are several differences among the two experiments: MiniBOONE will use a beam of approximately 30 times more energy and it will be located at about 20 times the distance of LSND; the Cerenkov light is 4 times larger than the scintillation light, and particle identification will be based on ring shape rather than relying on delayed neutron capture. The philosophy of this experiment is to aim at large electron signals in case LSND is correct; however, also the total number of events is large ($\approx$ 600000 CC events/year) and so are the backgrounds (see table 1 for details). After one year of running, the experiment will be able to either confirm or disprove the LSND result, hopefully solving by the beginning of 2003 one of the most important open problems in neutrino physics.

Table 1: Main background sources for the MiniBOONE experiment

Source	N. events/year
Misidentified pions	600
Misidentified muons	600
Intrinsic ν_e in beam	1800

3 The atmospheric region

The parameter space region with large mixing angle and mass difference squared of the order of $3 \times 10^{-3} eV^2$ is usually referred to as the atmospheric region, since the most natural explanation to the atmospheric neutrino anomaly is an oscillation governed by these parameters. In order to improve the already good present data, two approaches can be followed:

- a different "beam": the uncertainty on atmospheric neutrino production can be reduced using an artificial beam of neutrinos produced by an accelerator, with a baseline of several hundreds of kilometers
- different detectors: it is possible to aim at lower thresholds, better L/E resolution, more mass

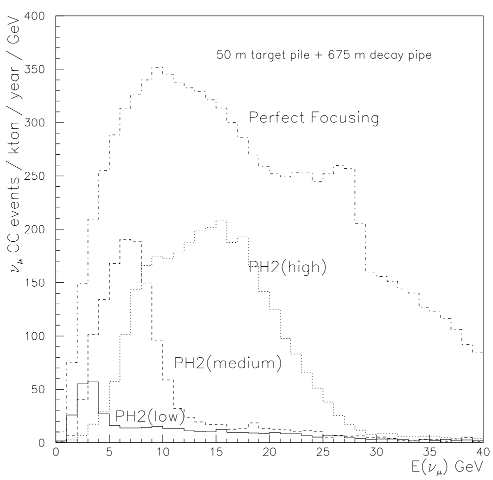

Figure 1: The three possible profiles of the NuMI beam. Given the present value of Δm^2_{23}, the low energy beam will be used.

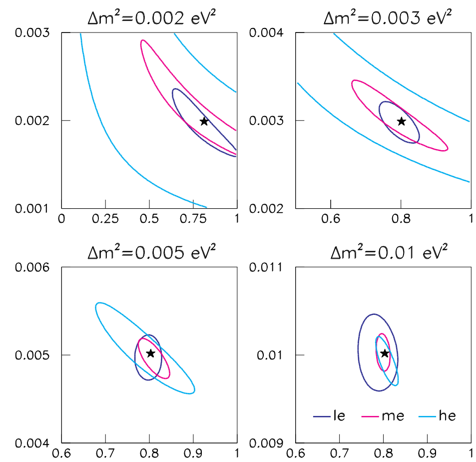

Figure 2: Precision on the determination of Δm^2_{23} and $\sin^2 2\theta_{23}$ for various values of the first parameter, setting the second at 0.8

The first long-baseline neutrino beam, the Japanese project K2K, has started data taking in 1999. For more details about this program and its results, refer to [6]. The other two beams are the American project NuMi from Fermilab to the Soudan site in Minnesota and the European CNGS from CERN to Gran Sasso. Their design is driven by to different philosophies, due to different physics goals and detector designs. The American experiment aims at a precision measurement of the oscillation parameters; a near detector is planned, and the beam has a tunable energy to have more events where the maximum of the oscillation should take place. On the contrary, the European experiment will be entirely devoted to τ search to confirm the $\nu\mu \rightarrow \nu_\tau$ nature of the atmospheric oscillations, and the beam profile will be tuned to produce the largest number of τ neutrinos in the detector.

3.1 MINOS

The MINOS detector will be a 5 kton coarse magnetized iron-scintillator apparatus, consisting of 486 layers of 2.54 cm thick iron slabs, interleaved by 1 cm thick scintillator strips read out by wavelength shifter fibers. Overall, there will be 25800 m^2 of active detector planes. The main measurement will be the precise determination of Δm^2_{23} and θ_{23} from ν_μ disappearance. The maximum of oscillations occurs for $1.27\Delta m^2 L/E_\nu = \pi/2$, corresponding to about 2 GeV for the baseline chosen and the central value of the atmospheric neutrinos, so the low-energy option for the beam has been chosen. The beam profile, together with the two further possible options, are shown in figure 1. The precision achievable in the oscillation parameters Δm^2_{23} and $\sin^2 2\theta_{23}$ is in 2.

The appearance search program from MINOS suffers from the poor detector granularity; $\nu_\tau \leftrightarrow \nu_s$ discrimination is possible on a statistical basis from the ratio of charged current-like and neutral current-like events. Also the sensitivity for $\nu_\mu \rightarrow \nu_e$ searches is limited by the detector electron identification capabilities, and for this measurement MINOS will be used in conjunction with the present SoudanII apparatus (that in this contest will be called THESEUS [8]).

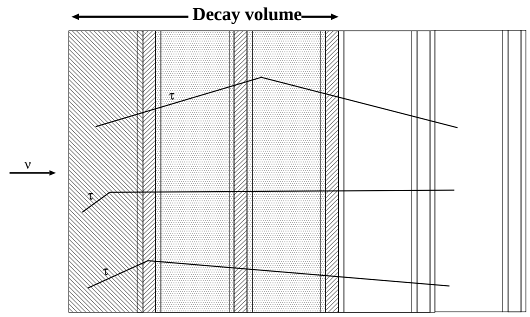

Figure 3: Possible τ decays in the OPERA lead-emulsion sandwich. From top: long decay, long decay in emulsion base, short decay.

3.2 OPERA

OPERA will be a dedicated experiment to look for τ appearance at the CNGS beam. Its design philosophy is to have an almost background-free experiment, such that even with few candidates it would be possible to claim discovery of $\nu_\mu \to \nu_\tau$ oscillations. To achieve this goal, the τ will be identified via the kink produced by its decay, exploiting the very high space resolution provided by nuclear emulsions. Due to their price, however, it is not possible to envisage a detector entirely made of emulsions; it will be made of a passive material (lead) used as a neutrino target, while the emulsion sheets will be used for tracking (see figure 3). τ production will be searched for in three decay channels: $\tau \to e$, $\tau \to \mu$ and $\tau \to h$. The τ produced from neutrino interactions will either decay in the same lead block (short decay, only used in the $\tau \to e$ channel) or in the neighboring one (long decay). In the first case, they are identified from tracks having large impact parameter with respect to the reconstructed vertex; in the second case, directly from the kink of the track. The total efficiency ($\times$ BR) is expected to be 8.7%. Main background sources are:

- cosmic rays and radioactivity from the rocks
- hadronic decays and re-interactions
- muon scattering
- charm decays

for an expected total of 0.57 events for 5 years of data taking. In the same period, the number of τ events expected is 4.1, 18.3 and 44.1 for $\Delta m^2_{23} = 1.5, 3.2, 5.0 \times 10^{-3} eV^2$, respectively[9].

3.3 ICANOE

Another approach to the τ search at the CNGS is proposed by the ICANOE experiment. The detector will be composed of four modules of large (1245 ton fiducial mass each) liquid Argon Time Projection Chambers, completed with an external muon spectrometer. Its very good imaging, particle identification and calorimetric capabilities offer a wide variety of physics possibilities. One of the main motivations for developing such a technology is the search for nucleon decay, for which a background-free search is possible, in particular for the SUSY-preferred channels (like $p \to K^+\bar{\nu}$). The detector is a very good next generation atmospheric neutrino experiment: it allows detection of all neutrino flavors, in NC and CC modes, with a much lower energy threshold and better L/E resolution than SuperKamiokande. Actually, a 600 ton ICARUS liquid Argon

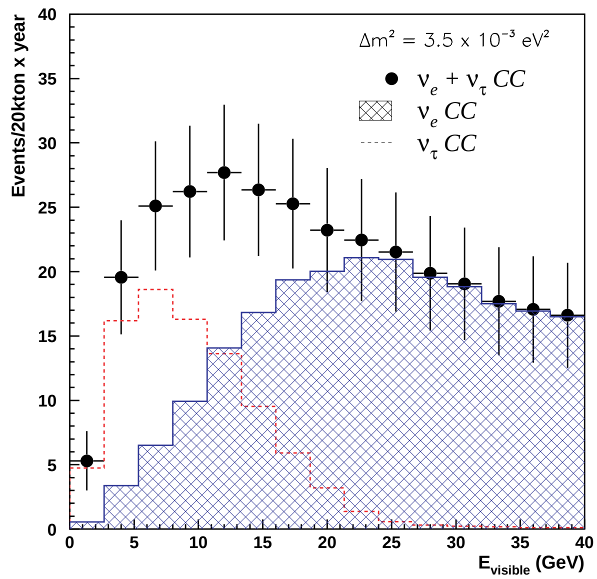

Figure 4: Visible energy for ν_τ events (red histogram) and ν_e background (dashed histogram). The sum of the two, with realistic statistical errors, is shown in crosses

detector will already be installed in Gran Sasso by the year 2001, and despite the smaller mass it will be able to cover the SuperK allowed region, due to the smaller energy threshold.

Another main physics topic is of course the study of neutrinos from the CNGS beam. This detector is able to perform $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_t au$ searches, exploiting the different kinematics of electrons from $\tau \to e$ decays and from electron neutrinos in the beam. As we can see in figure 4, already at the level of total visible energy the presence of τ neutrinos can be detected, and after kinematical cuts 37 ν_τ events are expected to be seen against a background of 4.4 for $\Delta m^2_{23} = 3.5 \times 10^{-3} eV^2$ after 4 years of data taking. Combining results from atmospheric neutrinos with those from the CNGS beam, it is possible to derive measurements of the oscillation parameters of the order of 10% for a reasonable choice of the parameters (Fig. 5 and 6).

3.4 Large atmospheric neutrino detectors

A post-SuperKamiokande atmospheric neutrino detector should have a better L/E resolution, to allow the observation of the oscillation dip in atmospheric events. This is the idea beneath the Monolith proposal for Gran Sasso [11], a large (34 kton) coarse calorimeter (120 8 cm thick iron plates alternated with 2 cm of gas spark chambers) with a 1T magnetic field. Given the coarseness of the apparatus, the detection of the hadronic part in charged current interactions is very difficult, and a good determination of the initial neutrino direction can be obtained only at high energy, where the correlation between neutrino and muon direction is quite strong. For this reason a 1.5 GeV cut on the muon energy is applied, that limits the statistics to about 7 events/kton/year. The large mass of the detector allows however to see the oscillation dip down to values of $\Delta m^2_{23} \approx 10^{-4} eV^2$ (figure 7).

Another possible solution for a next-generation atmospheric neutrino detector would be a follow-up of Super-Kamiokande, i.e. a giant (1 Mton) water Cerenkov. The interest in such a detector is mainly driven by the search for proton decay in the classic channel $p \to e^+ pi^0$. The study of atmospheric neutrinos would clearly be another main reason for building such a detector; however, already for the present SuperK data the systematic error has the same magnitude as the statistical error; moreover, price reasons would force a smaller photo-multiplier coverage, that could result in poorer particle identification capabilities, and still to be solved are the

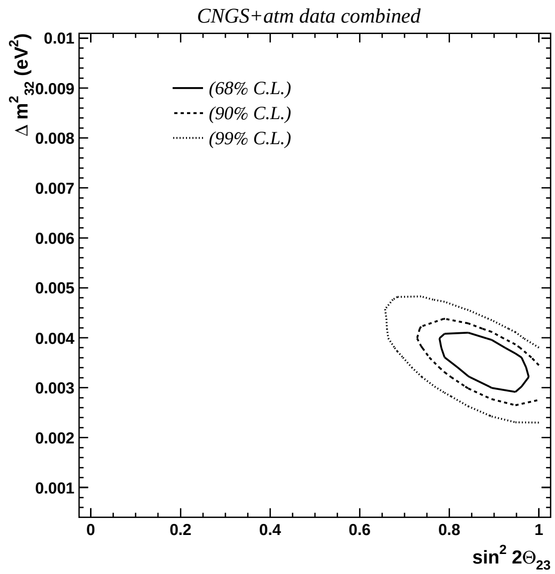

Figure 5: Precision on the measurement around the central values of $\Delta m^2_{23} = 3.5 \times 10^{-3} eV^2$ and $\sin^2\theta_{23} = 0.9$.

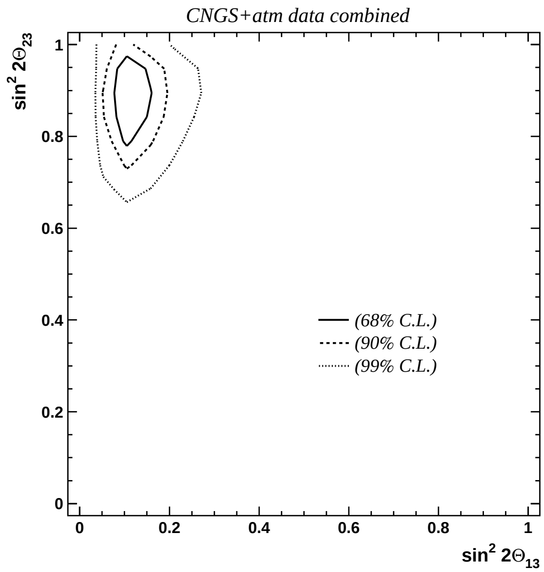

Figure 6: Precision on the measurement around the central values of $\sin^2 2\theta_{13} = 0.10$ and $\sin^2\theta_{23} = 0.9$.

problems connected with the large excavation time needed and the price of such an apparatus.

4 Looking at the future

In 10 years from now, if no particular surprise emerges, the situation of neutrino oscillation could be as follows:

- oscillations should be confirmed with an artificial beam by K2K, and the oscillation parameters measured with better accuracy by MINOS
- τ neutrinos from a ν_μ beam should be observed by the two CNGS experiments
- $\nu_\mu \to \nu_e$ oscillation could be observed by ICANOE, or a limit on $\sin^2 2\theta_{13} < 10^{-3}$ could be derived
- $\sin^2\theta_{23}$ and Δm^2_{23} measured with 10% precision

Goals for a next generation experiment would be:

- measurement of the parameters of the leading oscillation with O(1%) precision
- improvement of sensitivity on θ_{13}, i.e. on $\nu_m u \to \nu_e$ oscillations
- observation of matter effects on earth
- discovery of CP violation in the leptonic system.

To reach these ambitious goals, new tools are needed. In particular, many studies are going on to assess the physics potentials of a Neutrino Factory,[12] i.e. a machine where neutrino beams would be created from the decay of muons in a storage ring. The main advantage of this approach as opposed to "traditional" neutrino beams from proton decays are the fact that neutrino beams from muons would have only two flavors of different helicity and well-known spectra, while

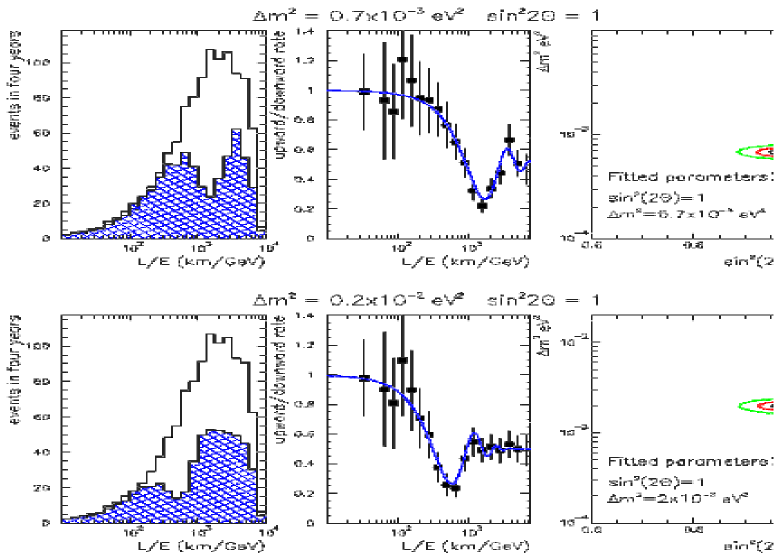

Figure 7: For two different values of Δm^2_{23}, from left to right: the energy spectrum without and with oscillations; the ratio of the two; the precision for measurement of the oscillation parameters.

beams from pion decay have all flavors (even a small ν_τ component), and their spectra are affected by uncertainties in hadronic production. In a neutrino factory, both muon charges would be possible, leading to the decays $\mu^- \to e^-\bar{\nu}_e\nu_\mu$, $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$, the muon energy could be tuned to have most of the events in an interesting region, and the beam could be polarized to enhance signal and control systematics. Since this machine is also envisaged as a first step towards a muon collider, high intensities are planned, of the order of 10^{20} muon decay per year. Such a high flux would assure a reasonable statistics also for very long baseline experiments, i.e. where the distance between neutrino production and detection is several thousands of kilometers. Given the atmospheric parameters, this would allow observing the dip of $\nu_\mu \to \nu_\tau$ oscillations at an energy of about 15 GeV, and perform a precision measurement of its oscillation parameters. A much improved precision can be reached in the search for $\nu_e \to \nu_\mu$ oscillations, looking for wrong-sign muons in the final state, i.e. muons with opposite charge with respect to those circulating in the ring. These events can only be originated by oscillations (with a very small small background from meson decays), in particular from the electron neutrino component of the beam. In this case, the unique possibility offered by the neutrino factory of running with either positive or negative muons in the ring offers the opportunity to study matter effects on earth [13], given the different interference term of electron neutrinos or antineutrinos interacting with the electrons inside the earth. This difference allows the determination of the sign of Δm^2_{23}, while all oscillations in vacuum or at shorter baselines are only sensitive to its absolute value. The spectrum of wrong-sign muons is also distorted by the presence of a complex term in the lepton mixing matrix, i.e. by the presence of CP violation in the leptonic sector. Figure 8 shows the asymmetry in the number of wrong-sign muon events due to matter effects and CP violation as a function of the chosen baseline.

5 Conclusions

Even after the latest results in experimental neutrino physics, much has still to be done to have a clear view of the mixing in the leptonic sector. The first aspect to be clarified is the validity of the LSND result, that still awaits an independent confirmation, and would need the introduction

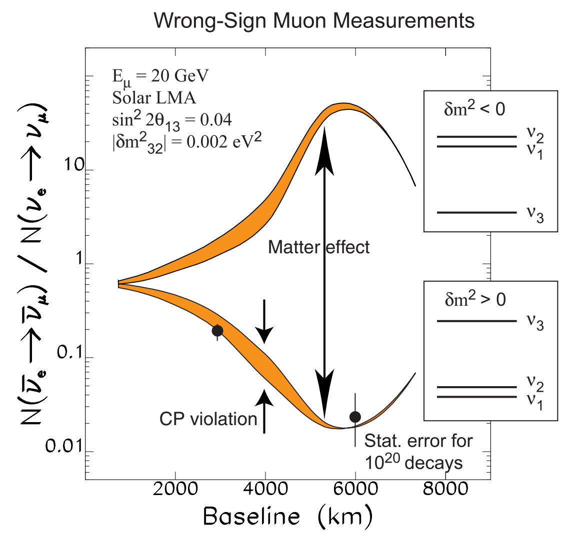

Figure 8: The ratio in the number of wrong-sign muons between runs with positive and negative muons in the ring. The two curves represent the two signs of Δm^2_{23}, and the tickness of the line represent the variation due to different values of the CP-violationg parameter δ_{13}.

of sterile neutrinos for its interpretation. The MiniBOONE experiment will explore this region, expecting large signals in case of validity of the LSND result, even if also backgrounds will be large.

The atmospheric region will be explored by long baseline neutrino beams in Japan, United States and Europe. They will confirm the disappearance of muon neutrinos (K2K), measure the oscillation parameters (MINOS), and confirm that the oscillation is mainly due to $\nu_\mu \to \nu_\tau$ transitions (OPERA/ICANOE). The ICANOE detector will also play a leading role to the search for $\nu_\mu \to \nu_e$ transitions.

After these experiments, a next generation of machines will be needed, to improve the precision of the measurements, to have more sensitivity on θ_{13} or discover $\nu_e \to \nu_\mu$ transitions, to study matter effects on earth and to possibly discover CP violation in the leptonic sector. For all these studies, the best solution is probably to build a Neutrino Factory where neutrinos are produced from the decay of stored muons. The high neutrino fluxes considered are essential for precision measurements, as well as for permitting very-long baseline experiments, that allow a detailed study of matter effects, and would open a window on CP violation in the leptonic sector.

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